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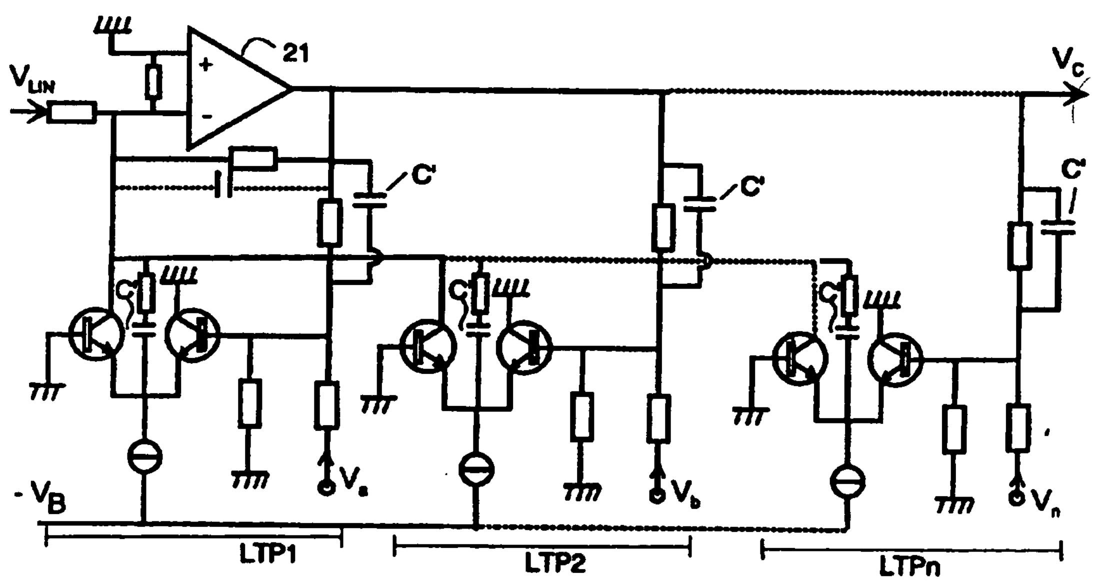

(57) Abstract

Non-linearity of a voltage-controlled non-linear amplifier/attenuator is compensated by placing a non-linear circuit in the feedback path of an operation amplifier (21) of a linearizer, the circuit comprising one or more differential amplifiers connected in parallel. For example, one amplifier (LTP1) can be a low-gain amplifier whose exponential range is at the lower end of the control voltage range (V_{LIN}), and another can be a high-gain amplifier whose exponential range is at the upper end of the control voltage range. When a necessary number (n) of differential amplifiers are used in the feedback path, it is possible to compensate for the non-linearity of the non-linear component to a desired extent.

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A LINEARIZER FOR LINEARIZING A NON-LINEAR COMPONENT CONTROLLED BY CONTROL VOLTAGE

The invention relates to a linearizer comprising an amplifier and a compensating non-linearity located in its feedback path. A linear control voltage applied to the input of the amplifier is transformed in the linearizer such that the non-linearity of the non-linear element controlled by the transformed control voltage is essentially compensated such that the output voltage of the non-linear element is essentially linearly dependent on the linear control voltage.

In radio unit transmitters, voltage-controlled components, such as RF attenuators and amplifiers, are used. The attenuation/amplification of these compenents in the adjustment range should be linearly dependent on the adjustment voltage. A typical embodiment is a power levelling loop in which the input power of an RF signal supplied to an amplifier of a transmitter is essentially a constant, and the power of a signal output from the amplifier must be adjusted over a wide range at submicrosecond speed. The characteristic of most voltage-controlled components is non-linear, i.e. without any specific linearization the attenuation G of the amplifier, i.e. the ratio of output voltage V_{out} to input voltage V_{in} as a function of control voltage V_c, is as illustrated by the graph of fig. 1. As the control voltage increases from zero, the graph first shows a leakage region 1, where attenuation G has a minimum value. It is almost independent of control voltage V_c. As the control voltage increases, a first linear transition region 2 follows. In this region, attenuation is a linear function of the control voltage. The next region is an exponential or dB-linear region 3, where attenuation is an exponential function of the control voltage. With a furth r increase in the

control voltage, a second linear transition region 4 follows. Here too attenuation is a linear function of the control voltage. The last region is a saturation region, where attenuation has a maximum value which is almost independent of the control voltage.

In most embodiments, a required property of voltage-controlled components is linearity. As previously known, this can be achieved by the use of a specific linearizer. The objective of the linearizer is to transform the linear control voltage supplied thereto to non-linear control voltage whose characteristic is inverse to the characteristic of the voltage-controlled component, whereby they combine to form a linear characteristic of a voltage-controlled component.

Fig. 2 shows the principle of a typical inverting linearizer known in the field. A non-linear circuit 22 is placed in the feedback path of a high-gain non-linear operation amplifier 21. The input of the amplifier is the voltage V_{LIN} to be linearized, and from the output is obtained non-linear control voltage V_c, which is supplied to a voltage-controlled attenuator/amplifier 23, where it compensates for non-linearity G.

In order that non-linearity G could be compensated, it should be either a monotonically ascending or monotonically descending function of control voltage V_c, whereby it can be represented by formula (1):

$$G(V_c) = g_{00} \pm g_{01}(A \bullet (V_c - V_{01})) = g_{00} \pm g_{01}(V_0) \quad (1)$$

where g_{00} is a constant and g_{01} is a monotonically ascending function. V_{01} is an offset term and A is a scaling factor, which are used for expressing non-linearity G as a function of voltage V_0. The non-linear

circuit 22, which can be called a compensating non-linearity, produces a feedback current $I_0 = I_{00} \pm I_{01}(V_0)$, where I_{00} is a constant part and I_{01} is a part dependent on voltage V_0. Voltage V_0 is obtained from output voltage V_c by scaling by A and offsetting by V_{01}. The scaling and offsetting can be performed with resistor networks. The plus sign is used when the amplifier is a non-inverting amplifier, and the minus sign when it is an inverting one. Non-linearity I_{01} is called the compensating non-linearity, whereas function g_{01} can be called the non-linearity to be compensated. If the amplifier 21 has infinite gain, it will try to make the voltages at the input poles equal, so that the following equation holds true:

$$V_{LIN} = (I_{00} \pm I_{01}\ (V_0))R \qquad (2)$$

When the above is compared with formula (1), we see that G is a linear function of V_{LIN} if $I_{01}\ (V_0)$ is a linear function of $g_{01}(V_0)$. Terms I_{00} and g_{00} have no effect on the linearization, but they cause a fixed offset, whereby the compensation requirement for I_{01} is

$$I_{01}(V_0) = p+q-g_{01}(V_0),$$

where p and q are arbitrary constants.

The tendency in modern voltage-controlled attenuators is to make the exponential range (i.e. dB-linear region) as large as possible and to minimize the linear range. In some attenuators, the second linear region 4, fig. 1, is very narrow, and in some places the gain in region 3 rises even more than exponentially. The known linearizers, such as those previously presented by the inventor of the present invention, do not enable linearization of such non-linear components

in the entire characteristic, especially not in regions 2, 3 and 4 of the curve shown in fig. 1.

The object of the present invention is to provide a linearizer without the drawbacks of the known solutions. The object is to provide a non-linear circuit whose characteristic in as wide a region as possible is the same as the characteristic of the non-linearity to be compensated.

The above object is achieved by a circuit as described in claim 1.

In the invention, the non-linear implementation of a circuit, i.e. of the compensating non-linearity, is based on a known differential amplifier according to fig. 3, the amplifier being called below an LTP (Long Tailed Pair). Transistors Q_1 and Q_2 are matched pairs, collector current I_1 of transistor Q_1 is the desired current I_{01} ($I_1 = I_{01}$), and the collector current of transistor Q_2 is $I_2 = I_t - I_{01}$. An LTP like this produces the non-linearity of formula (3):

$$I_{01} = 1/2 \cdot I_t \cdot (1+\tanh(V_0/2V_T)) \qquad (3)$$

where I_t is a tail current, which is the current I_t of a constant-current source and simultaneously the sum of the collector currents, and V_t is a voltage proportional to the absolute temperature, being about 26 mV at room temperature. Reference number 31 indicates a current generator that produces constant current I_t. In the other figures, the current generator is indicated by the same symbol. The linear region of the graph of one LTP (not shown), however, is large as compared with the exponential region, which is not sufficient to compensate the large non-linear region. In the invention, a non-linear circuit to be placed in the feedback path of the operation amplifier is formed by

combining at least two LTPs, one of which is a low-gain LTP whose exponential region is at the lower end of the control-voltage region, and the other is a high-gain LTP whose exponential region is at the upper end of the control-voltage region. In a non-linear circuit, the non-linearity of a non-linear component can be compensated to a desired extent by the use of a necessary number of LTPs.

In one embodiment of the invention, one uses a modified LTP where an additional transistor is connected in parallel to the transistors of the basic connection, the collector of the additional transistor being connected to the collector of one transistor of the basic connection and its emitter being connected to the emitters of the basic connection. The voltage affecting at the base of the additional transistor is output voltage V_c of the operation amplifier, although it has been offset and scaled independently. This connection will be called below an LTP-plus. The non-linearities of the LTP-plus are almost the same as those of a combination of two LTP amplifiers, but it has some drawbacks, which will be discussed below.

In the following, the invention will discussed in greater detail by means of a preferred embodiment of the invention with reference to the attached drawings, in which

fig. 1 shows a typical characteristic of a voltage-controlled attenuator,

fig. 2 illustrates a known principle of a linearizer,

fig. 3 illustrates an LTP,

fig. 4 illustrates a combination of two LTPs,

fig. 5 illustrates a combination of three LTPs,

fig. 6 illustrates an LTP-plus,

fig. 7 illustrates a linearizer comprising a non-

linear circuit according to the invention, and

fig. 8 illustrates a linearizer comprising a modified non-linear circuit.

In fig. 4, the LTPs, which form the compensating non-linearity element of the feedback path shown in fig. 2, are connected in parallel such that the input of both LTPs is control voltage V_c. At each pair, control voltage V_c is subjected to individual scaling (A_a, A_b) and level shifting ($-V_{0a}$, $-V_{0b}$). The sum of input currents I_{01a}, I_{01b} of the left-hand-side transistors in the pairs, at the base of which control voltage V_c has a functional effect, is I_1, and the sum of the input currents of the right-hand-side transistors is I_2. A pair of amplifiers is connected to the feedback path of a linearizer in a manner described below (fig. 2) such that the feedback current is I_2. It is also possible to use current I_1 as the feedback current, but the signs of the input poles of the operation amplifier should then be changed in the connection illustrated in fig. 2. This produces a non-inverting linearizer, which, however, has a drawback mentioned below.

In the graph (not shown) of the connection illustrated in fig. 4, the exponential region, i.e. the region where the derivative of current I_1 in relation of voltage V_c divided by current I_1 is a constant, i.e.

$$\frac{1}{I_1}\frac{dI_1}{dV_C}$$

is a constant, is significantly larger than with the single LTP connection of fig. 3.

Any desired number of LTPs can be connected in parallel. Each LTP compensates for its own part of non-linearity, whereby the use of a sufficiently large number of LTPs makes it possible to make the linearity

to be compensated as accurat as desired. The use of three LTPs in accordance with fig. 5 makes it possible to produce a large number of different non-linearities. The non-linear circuit of fig. 5 is sufficient for most embodiments.

The use of several LTP amplifiers is advantageous in many ways: for example, adjustment parameters A_n and V_{0n} of each pair have an independent effect, i.e. they do not affect the operation of the other pairs, and the linearity obtained is not very sensitive to any single adjustment parameter. In addition, the circuit can be easily integrated as an analogue IC.

An LTP amplifier can be modified in the manner shown in fig. 6. In the figure, an additional transistor Q3 is connected in parallel to transistor Q1 of the basic LTP, the collector of the former transistor being connected to the collector of the latter LTP transistor Q1, and its emitter being connected to the emitters of the transistors of the basic connection. The voltage affecting at the base of additional transistor Q3 is the same voltage V_c as at the base of the LTP transistors, except that it has been independently offset by term $-V_a$ and scaled by scaling factor A_a. In the following, this connection will be called an LTP-plus.

The non-linearity properties of the LTP-plus are almost the same as those of a combination of two LTP amplifiers. However, it is more difficult to design, since the adjustment parameters affect one another. Further, the connection is more sensitive to the tolerances and temperatures of the components than a circuit of two LTPs.

In practice, linearization circuits have a flat region in the curves of current I_{01} of the feedback path. This is problematic, since it means that the

operation amplifier has no feedback in this region. The situation worsens if I_{01} decreases simultaneously as V_c rises very high. This, however, happens only in a non-inverting linearizer when V_c rises so high that the base-collector junction of one of the transistors becomes conductive. This may result in loss of the operating capacity of the linearizer. Because of this, it is not recommendable to use long tailed pairs in a non-inverting linearizer. In an inverting linearizer, even the flat regions are easier to deal with. Further, it has been observed in real voltage-controlled attenuators that they are never completely flat in their useful operating ranges. It is thus possible to place a large resistor between the output of an operation amplifier and an inverting input, as shown in figs. 7 and 8. This imitates the first linear region 2 in a typical characteristic of a voltage-controlled amplifier, as shown in fig. 1.

Figs. 7 and 8 show a non-linear circuit of the invention in a linearizer. Fig. 7 shows an inverting linearizer with several LTPs, whereas fig. 8 shows a linearizer with an LTP-plus. Voltage V_B is the operating voltage of the non-linear circuit. The figures show inverting amplifiers, but a circuit with non-inverting ones is obtained by interchanging the plus and the minus input of the amplifier, and by using, in the feedback, the collectors of those transistors which are grounded in the figure. Linear feedback, however, has to conducted to the negative input of the amplifier, i.e. the large resistor will have to be placed between the output of the operation amplifier and the inverting input. A non-inverting structure, however, is not recommended for the reasons stated above. It is also possible to use circuits implemented with PNP transistors. In all these circuits, current source I_t

can be replaced with a r sistor and a suitable voltage source.

Fig. 7 also illustrates ways of modifying the frequency response of the linearizer. To make the frequency response as direct as possible and prevent the circuit from vibrating at just any control voltage, frequency compensation that is dependent on the operating point is needed. It can be implemented by connecting capacitors to the non-linear element. The capacitors are indicated generally in the figure by C'.

In figs. 7 and 8, voltages $-V_{0n}$ are normally supply voltages, depending on the fact whether a positive or negative offset is needed. In each LTP of the figures, it is possible to replace the offset supplied to the base of the right arm with the offset supplied to the base of the transistor in the left arm, the latter offset having the opposite sign. In practice, however, it is preferable to connect the base of the transistor in the left arm to the ground.

It is to be understood that the above specification and the associated figures are only intended to illustrate the present invention. It will be obvious to one skilled in the art that the invention can be varied and modified in many ways without deviating from the scope and spirit of the invention presented in the attached claims.

Claims

1. A linearizer for linearizing a non-linear component controlled by control voltage, the linearizer transforming linear control voltage (V_{LIN}) to non-linear control voltage (V_C), and the linearizer comprising

a feedback amplifier (21), to the input of which is applied the linear control voltage (V_{IN}), and from the output of which is obtained the non-linear control voltage (V_C),

a non-linear circuit (22) placed in the feedback path, the non-linearity of the circuit being mainly the same as the non-linearity of the voltage-controlled non-linear component,

characterized in that the non-linear circuit (22) comprises at least one differential amplifier formed of a matched pair of transistors (Q1, Q2), the amplifier being connected such that in the pair:

the base of the first transistor (Q1) is functionally connected to the output of the feedback amplifier, whereby the collector current (I_1) of the first transistor depends on the voltage of the output of the feedback amplifier,

the base of the second transistor (Q2) is functionally grounded,

the emitters of the transistors are connected together, and the common emitter current is essentially a constant, whereby a change in the collector current of the first transistor causes an opposite change in the collector current (I_2) of the second transistor,

the collector of the second transistor (e.g. Q1) is connected to the input of the feedback amplifier, and the collector of the second transistor (e.g. Q2) is connected to the ground.

2. A linearizer according to claim 1, c h a r a c t e r i z e d in that an additional transistor (Q3) is connected in parallel to the differential amplifier such that its collector and emitter are connected, respectively, to the collector and emitter of the first transistor (Q1), and that the base of the additional transistor is also functionally connected to the output of the feedback amplifier.

3. A linearizer according to claim 1 or 2, c h a r a c t e r i z e d in that several differential amplifiers are connected in parallel such that the output voltage (V_c) of the feedback amplifier supplied to the base of the first transistor of each pair is subjected to individual scaling (A) and individual level shifting (V_n).

4. A linearizer according to claim 1 or 2, c h a r a c t e r i z e d in that the emitters of the transistors of the differential amplifier, which are connected together, are connected to a constant-current source (I_t).

5. A linearizer according to claim 3, c h a r a c t e r i z e d in that the non-linearity graph of the non-linear circuit is modified by individual scaling and level shifting to correspond to the non-linearity graph of the non-linear component to be linearized, whereby each differential amplifier compensates for its own part of the non-linearity of the non-linear component.

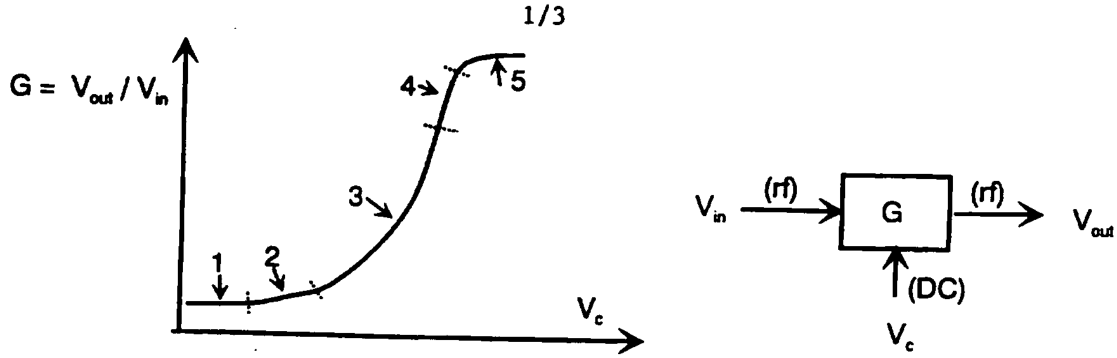


Fig. 1

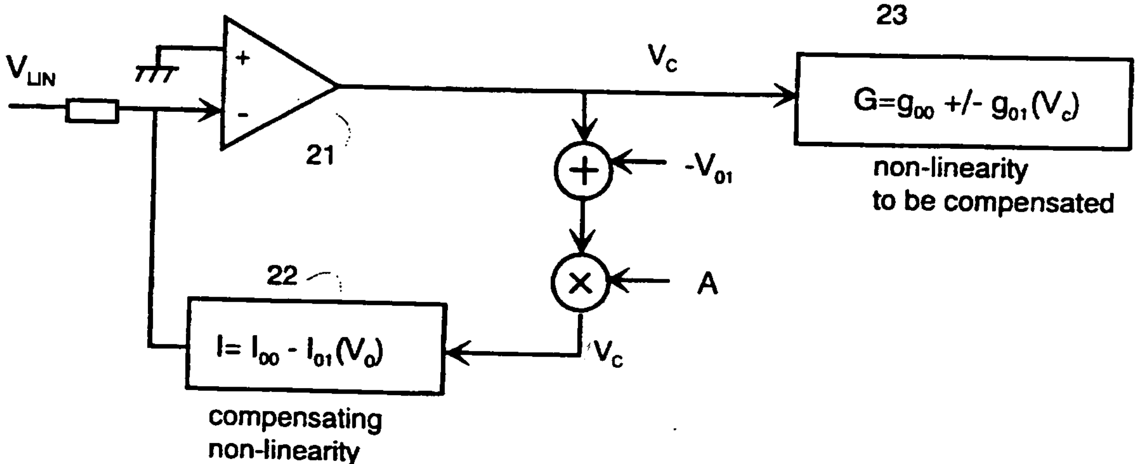


Fig. 2

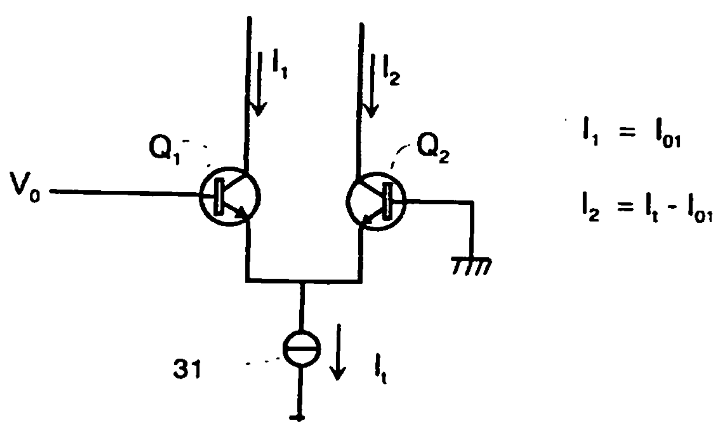
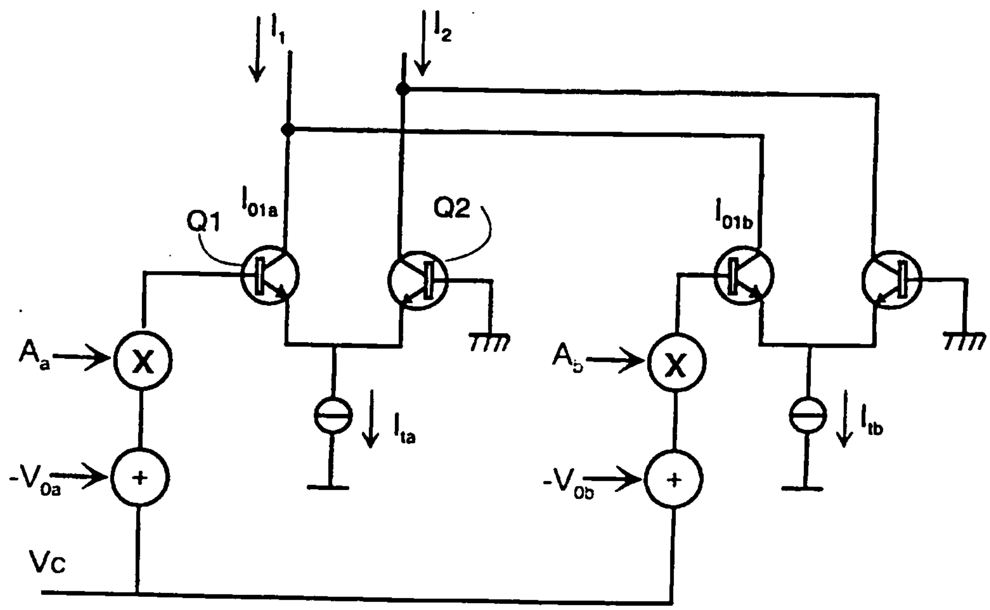


Fig. 3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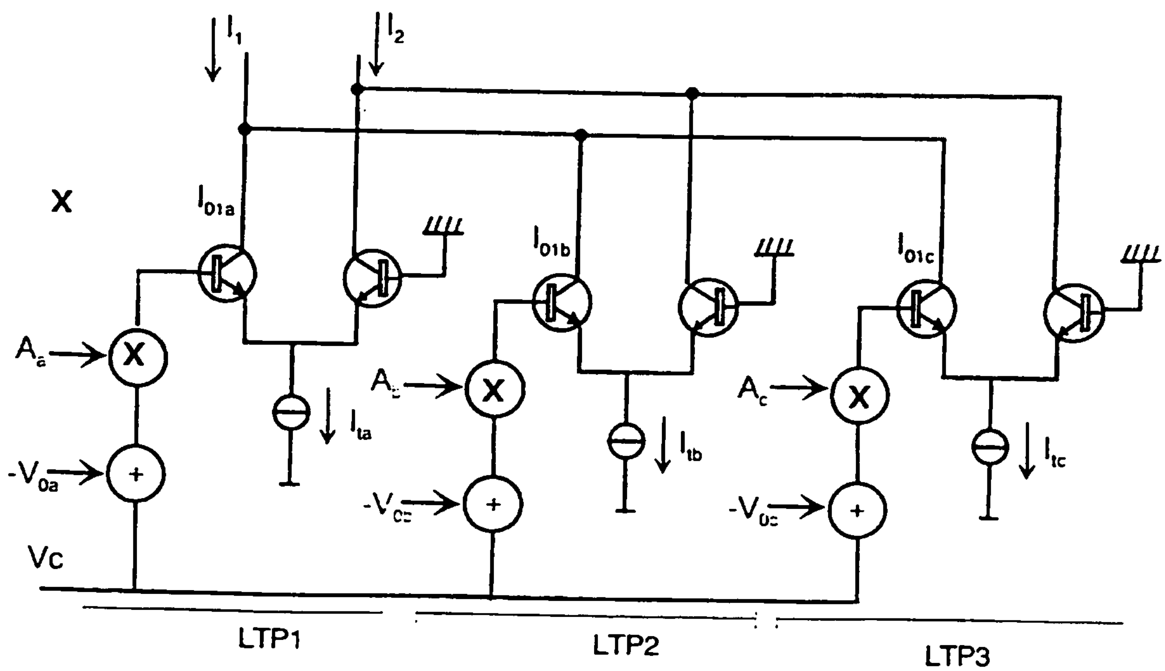
I2
Q1
I01a
Q2
I01b
Aa
X
Ab
X
Ita
Itb
-V0a
+
-V0b
+
Vc

Fig. 4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I2
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I01a
I01b
I01c
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Vc
LTP1
LTP2
LTP3

Fig. 5

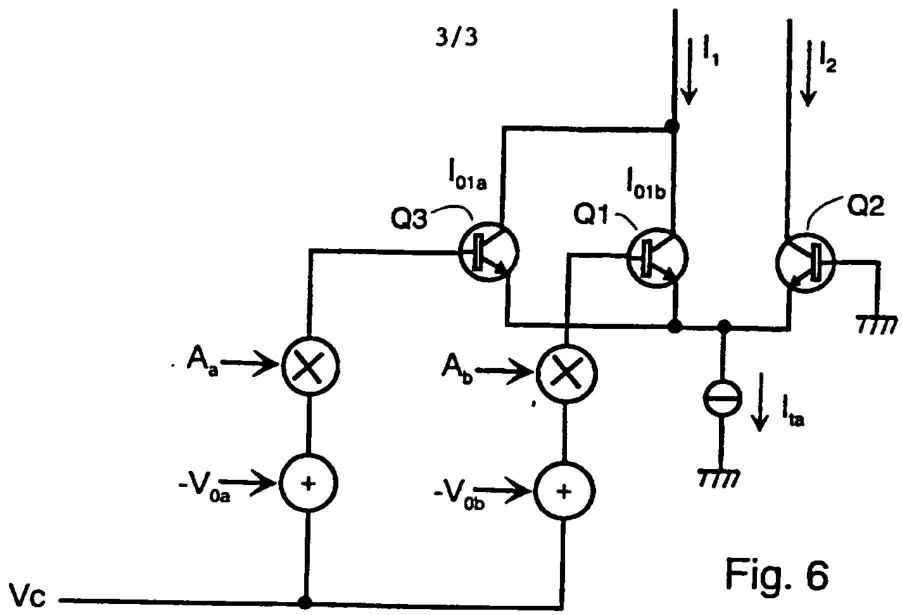

Fig. 6

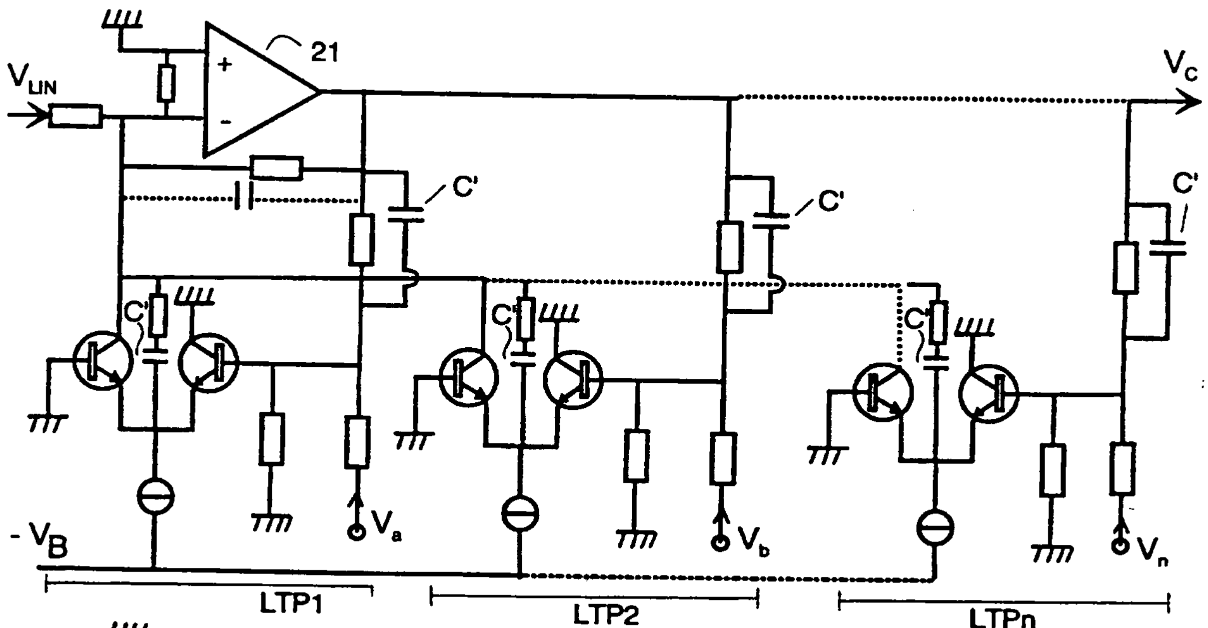

Fig. 7

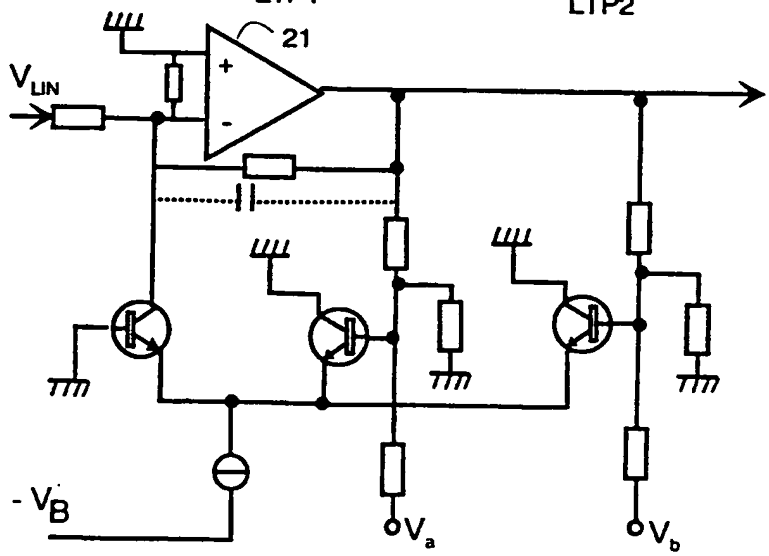

Fig. 8